INEEL/CON-00-01240
PREPRINT

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June 24, 2001

94th Annual Meeting and Exhibition of the Air and Waste Management Association

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Abstract #254

ABSTRACT

In 1998, 3.6 trillion kilowatt-hours of electricity were generated in the United States. Over half of this was from coal-fired power plants, resulting in more than 8.3 million tons of nitrogen oxide (NO_x) compounds being released into the environment. Over 95% of the NO_x compounds produced during coal combustion are in the form of nitric oxide (NO). NO_x emission regulations are becoming increasingly stringent, leading to the need for new, cost effective NO_x treatment technologies. Biofiltration is such a technology. NO removal efficiencies were compared in compost based biofilters using four different composts. In previous experiments, removal efficiencies were typically highest at the beginning of the experiment, and decreased as the experiments proceeded. This work tested different types of compost in an effort to find a compost that could maintain NO removal efficiencies comparable to those seen early in the previous experiments. One of the composts was wood based with manure, two were wood based with high nitrogen content sludge, and one was dairy compost. The wood based with manure and one of the wood based with sludge composts were taken directly from an active compost pile while the other two composts were received in retail packaging which had been out of active piles for an indeterminate amount of time. A high temperature (55-60°C) off-gas stream was treated in biofilters operated under denitrifying conditions. Biofilters were operated at an empty bed residence time of 13 seconds with target inlet NO concentrations of 500 ppmv. Lactate was the carbon and energy source. Compost was sampled at 10-day intervals to determine aerobic and anaerobic microbial densities. Compost was mixed at a 1:1 ratio with lava rock and calcite was added at 100g/kg of compost. In each compost tested, the highest removal efficiencies occurred within the first 10 days of the experiment. The wood based with manure peaked at day 3 (77.14%), the dairy compost at day 1 (80.74%), the active wood based with sludge at day 5 (68.15%) and the inactive wood based with sludge at day 9 (63.64%, this compost was frozen when received). These levels gradually decreased throughout the remainder of the experiment until they fell between 40% and 60%. Decreasing removal efficiency was characteristic of all the composts tested, regardless of their makeup or activity state prior to testing. Although microbial densities and composition between composts may have differed, there was little change in densities within each experiment.

INTRODUCTION

The demand for electricity in the United States continues to rise each year. Net electricity generation in the U. S. increased by an average of 2.3% per year between 1990 and 1998[1]. In 1998, a record 3.6 trillion kWh of electricity was generated which represented a 3.5% increase over 1997 levels. In 1998, over 70% of the electricity generated was from fossil fuels (primarily coal), totaling 2.54 trillion kWh. In 1998, the production of electricity from coal in the U. S. resulted in 8.3 million tons of nitrogen oxides (NO_x) being released into the atmosphere, or 34% of the total amount of NO_x released from all sources[2]. Most of the NO_x compounds (95%) released in the combustion of fossil fuels are in the form of nitric oxide (NO). NO is a reactive gas that contributes to a number of environmental and health problems including acid rain formation and the formation of ground level ozone[3].

Because of the risk to the environment and human health, there are a number of state and Federal regulatory initiatives that aid in the reduction of NO_x compounds generated. Title IV of the Clean Air Act Amendments of 1990 provides a stepwise method for electric utilities to reduce NO_x levels 2 million tons below 1980 levels by the year 2000. Phase I of the CAA Amendments calls for a reduction of 400,000 tons per year between 1996 and 1999. Phase II calls for a reduction of 1.17 million tons per year starting in 2000. The electric utilities have been given the freedom to select their own methods of NO_x control. This was intended to promote technology development and competition.

With these new stringent regulations in place, it becomes necessary to develop new technologies to reduce NO_x emissions from fossil fuel power plants. Since most power plants were constructed before these regulations were enacted, it is essential to develop technologies that can be retrofitted to existing facilities. NO_x control strategies can be divided into two categories: combustion control methods and post-combustion control methods. A low NO_x boiler is a commonly used combustion control method that modifies combustion methods to reduce NO_x formation. Post-combustion control methods remove NO_x from the gas stream after it has already formed. This includes technologies such as selective catalytic reduction (SCR) and biofiltration. SCR is the most widely applied post-combustion control method[4], however the system is subject to decreased efficiency due to catalyst fouling and formation of ammonium sulfate that can clog downstream equipment.

Biofiltration is a post-combustion control method that has shown promise. Biofilters have historically been used to treat large volume, low concentration gas streams containing readily biodegradable contaminants. Biofilters packed with soil[5] or compost[6-10] have been shown to remove NO_x from a gas stream both aerobically and anaerobically. Researchers at the Idaho National Engineering and Environmental Laboratory (INEEL) have been investigating the feasibility of anaerobic biofiltration in the removal of NO_x. Compost based biofilters operated under denitrifying conditions have been able to remove up to 90% of a 500 ppmv NO stream with an empty bed residence time of 1.3 min[7].

In order for compost based biofiltration to be a financially viable technology, biofilters must be capable of long term, high efficiency operation. In continuing the biofiltration research at the INEEL, it was found that while initial removal efficiencies can be high, efficiencies tend to decrease with time. As an example, in an experiment run under constant conditions, removal efficiencies decreased from about 80% to about 40-50% after 30 days[8].

The purpose of the current study was to study whether the source of compost used as biofilter bed medium influences these decreasing NO removal efficiencies that have been noted with time. To test this, four different compost types from three sources were evaluated in biofilters for NO removal under denitrifying conditions. Results of the comparisons are discussed below.

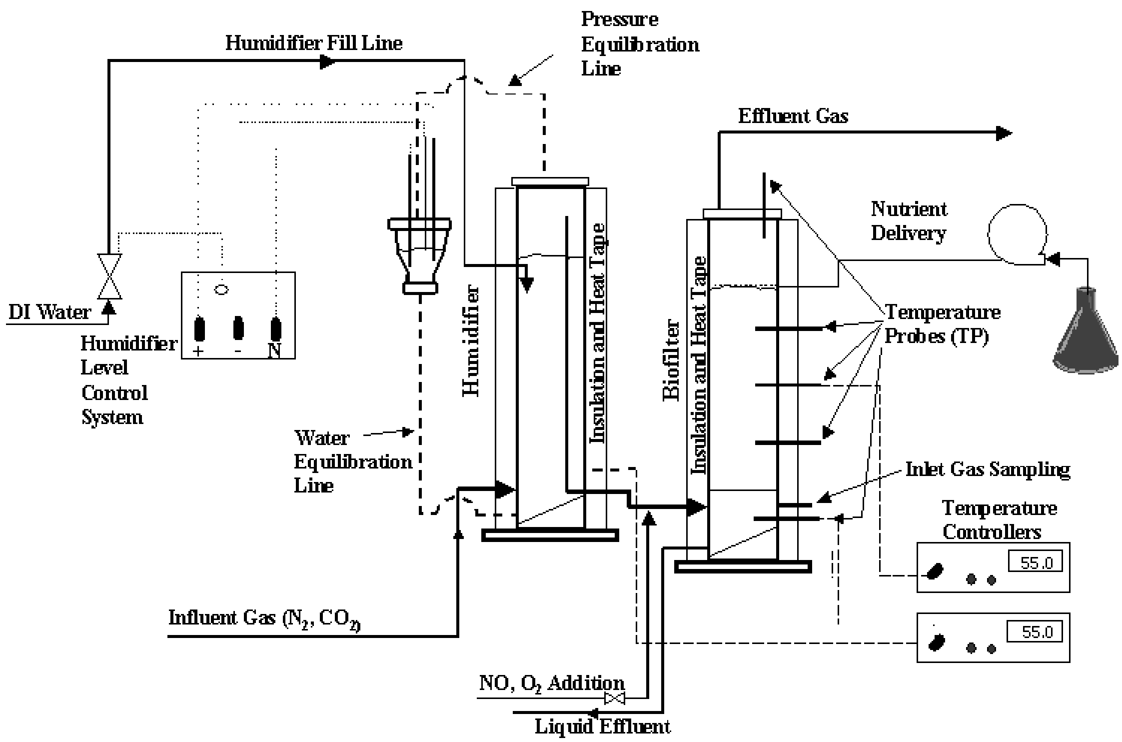
EXPERIMENTAL

Biofilter Bed Medium. The following experimental design was used for each compost tested. Two biofilters (BF1 and BF2) were filled with bed medium consisting of 50% compost and 50% crushed lava rock on a mass basis. To maintain neutral pH during the experiment, 100g calcite was added for each kilogram of compost/lava rock mixture. Compost was sieved using a number 10 sieve (2 mm screen) and a number 3/8 sieve (9.5 mm screen). The smallest particles were removed to keep the pressure drop in the biofilters low and the largest particles were removed to keep the surface area high. Biofilters were filled with 2.47×10^{-3} m^3 of the compost packing mixture.

The four compost types used for the packing were received from three sources. One was a wood based compost with manure from Nature Grow Compost (NGC) near Pocatello, ID. This was taken from an active compost pile and used within three days. Two others were wood based composts containing high nitrogen content sludge and were received from Glacier Gold Compost in Olney, MT. One was received in retail packaging (GG1) and had been frozen prior to use. It had been out of an active compost pile for an indeterminate amount of time. The other was taken from an active compost pile (GG2) and used within three days. The fourth compost was a dairy compost from Mountain Dairy Compost (MD) in Duchesne, UT. This was also received in retail packaging and had been out of an active compost pile for an indeterminate amount of time.

Biofilter Apparatus. A schematic of the biofiltration system can be seen in Figure 1. This setup was similar to that used in Lee et al.[9] with some exceptions. Mass flow controllers were used to regulate the flow of N_2, CO_2 (Cole-Parmer, Niles, IL), and NO (Sierra Instruments, Monterey, CA) to the biofilters. Nitric oxide was delivered from a compressed gas cylinder containing 99% pure NO (Norco, Inc., Boise, ID).

Figure 1: Biofilter schematic.



Biofilter Operation. Biofilter operation was similar to that in Lee et al.[9] with some exceptions. Biofilters were operated for a minimum of 30 days. Occasionally the pressure drop would become too high (>0.5 inches of water) and NO removal efficiencies would decrease. The increases in pressure drop were normally attributed to heavy saturation of the biofilter packing material. This condition was resolved by running the biofilters in reverse flow mode for about 4 hours using a dehumidified gas stream. Temperature settings were then adjusted to reduce the amount of humidity in the biofilter while maintaining the temperature and anaerobic conditions.

Microbial Analysis. Samples of the bed medium were analyzed for microbial density at time zero and after 10, 20, and 30 days of operation. Time zero samples were taken from the bulk compost prior to loading the biofilters. Bed medium samples were taken from 7.62, 15.24, and 22.86 cm over the length of the bed, for the latter three sampling dates. Samples were serially diluted and plated onto 1/10 strength trypticase soy agar (TSA) with 0.1% potassium nitrate as the electron acceptor. Plates were incubated at 55°C in aerobic and anaerobic environments. After two days, plates were removed and colonies were counted to estimate microbial densities in the biofilters. Microbial data was not collected for NGC.

Analytical. Biofilters were monitored daily for inlet and outlet NO concentrations, temperature, liquid effluent volume, pH, methane production, influent oxygen, pressure drop, and influent and effluent organic acid concentrations. A Bendix Model 8101-C Oxides of Nitrogen Analyzer (Dasibi Environmental Corp., Glendale, CA), using a flow injection type analysis was used to monitor NO in the biofilter influent and effluent.

Samples were taken using 50 μL gas sampling syringes (Hamilton, Inc., Reno, NV). The instrument uses a chemiluminescence detection system.

Concentrations of organic acids (e.g., lactate, acetate, propionate, butyrate and formate) in the influent and effluent were determined using a high-pressure liquid chromatograph (HPLC). The Hitachi (San Jose, CA) HPLC system was equipped with a D-6000 computer interface and UV detector (L-4000H) set at 210nm. Eluent (0.05N H_2SO_4) was pumped with a L-6200A Intelligent Pump at 0.375 ml per minute and an AS-4000 Intelligent Autosampler was used. The system was controlled by the Hitachi D-6000 HPLC Manager software, Ver. 2, Rev. 10. Organic acids were separated using a Brownlee, Polypore H, 10μ, 220 mm x 4.6 mm column. Column temperature was maintained at 35°C. Samples from the liquid feed reservoir and liquid effluent were diluted as necessary, acidified using 4N H_2SO_4 and filter sterilized using 0.2 μm nylon syringe tip filters (Gelman Sciences, Inc., Ann Arbor, MI) prior to analysis. Effluent organic acid concentrations were normalized to compensate for effluent volume using the following equation: ([OA]*EF/IF) where [OA] is the measured organic acid concentration, EF is the effluent flow rate, and IF is the influent flow rate.

Samples of each compost type as received from the supplier were sent to Western Laboratories, Inc. (Parma, ID) for soil analysis.

RESULTS AND DISCUSSION

Results have been separated by experiment. Occasionally the CO_2 would run out and biofilters would be without the gas for as long as 3 days. As a result, NO removal efficiencies and methane production would both decrease. These events are detailed in the following sections. Both measurements would recover after CO_2 was added back into the gas make-up.

Results from the soil analysis are summarized in Table 1. The results from the analyses performed related to pH, total iron and the carbon to nitrogen ratio are potentially relevant to the compost's function as a biofilter bed medium. Both samples of compost obtained from Glacier Gold showed lower pH and carbon to nitrogen levels than the other two compost types. Iron levels were also higher in the Glacier Gold compost, which might be important because iron and nitrate reducing organisms grow in overlapping redox zones. The pH of the Glacier Gold compost was also considerably lower than the Nature Grow and Mountain Dairy composts.

Table 1: Compost Analysis.

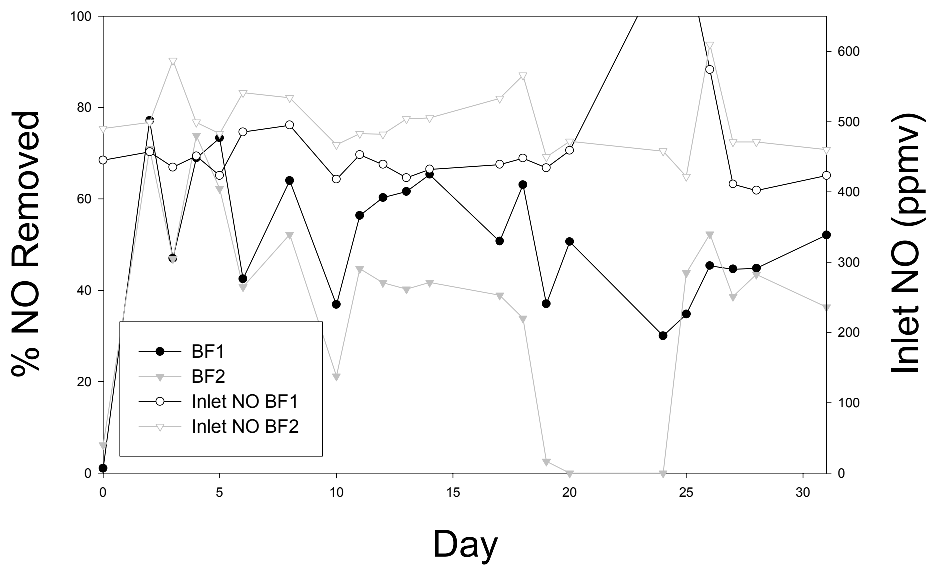
	Units	NGC	GG1	GG2	MD
Nitrogen	%	1.2	1.1	1.1	1.7
Phosphorous	%	1.00	1.06	0.953	1.18
Potassium	%	1.49	0.75	0.87	6.46
Calcium	%	6.59	1.43	1.11	7.8

Magnesium	%	0.64	0.38	0.33	1.55
Sodium	%	1.64	1.14	1.35	17.94
Zinc	mg/L	84.0	233.1	110.6	93.1
Copper	mg/L	1.53	12.03	5.36	4.97
Manganese	mg/L	324.9	184.6	140.22	215.46
Iron	mg/L	695.84	2385.92	1377.28	901.12
Boron	mg/L	30.29	9.87	6.42	115.57
Sulfate	%	0.2888	0.1144	0.1608	1.26
pH		8.2	5.4	5.7	9.6
C : N		36:1	9:1	4:1	17:1

Nature Grow Compost (NGC), Pocatello, ID

***NO Removal Efficiency**:* NO removal efficiencies were variable throughout the experiment (Figure 2). Removal efficiencies in BF1 peaked by day 2 (77.14%) and

Figure 2: NO removal efficiency
Nature Grow Compost

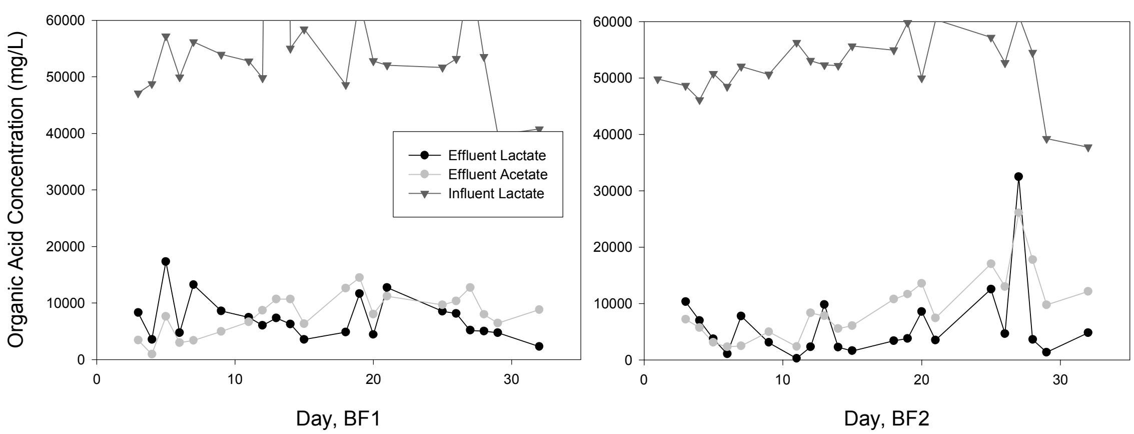


efficiencies in BF2 peaked by day 4 (73.87%). CO_2 ran out on days 3, 6, and 10, evidenced by sharp decreases in NO removal efficiencies. Removal efficiencies were initially high in both biofilters, but slowly decreased throughout the experiment. This decrease was more pronounced in BF2. On day 18 (after sampling had been completed), air was introduced into BF2 to bring oxygen levels in the gas mixture up to 8%. Oxygen levels remained at 8% for six days and then were turned off. Addition of oxygen was done in an attempt to stimulate growth of the denitrifying population in the compost. The hypothesis driving this change was that since denitrifiers are facultative anaerobes and preferentially use oxygen allowing for better growth. Once the microbial numbers had increased then the oxygen would be turned off, allowing for denitrification to be reestablished using more NO for growth. Although there was initially an increase in NO removal efficiency after the oxygen was turned off, removal levels never exceeded 60%.

pH of Liquid Influent and Effluent: The pH of the influent feedstock remained fairly constant as expected. Small fluctuations in the influent pH were due to small differences in batches of the feedstock. The pH of the effluent streams was more dynamic. Variations occurred early in the experiment as the biofilters acclimated to the high heat, humidity and anaerobic conditions. Once acclimated, pH levels remained close to neutral with few exceptions. One exception occurred in BF2 on day 20 and seems to coincide with the introduction of oxygen into the biofilter.

Organic Acid Analysis: Lactate concentrations of the influent feedstock in both biofilters were usually between 50 and 60 g/L for the first 28 days of the experiment (Figure 3).

Figure 3: Influent and effluent organic acid concentrations Nature Grow Compost

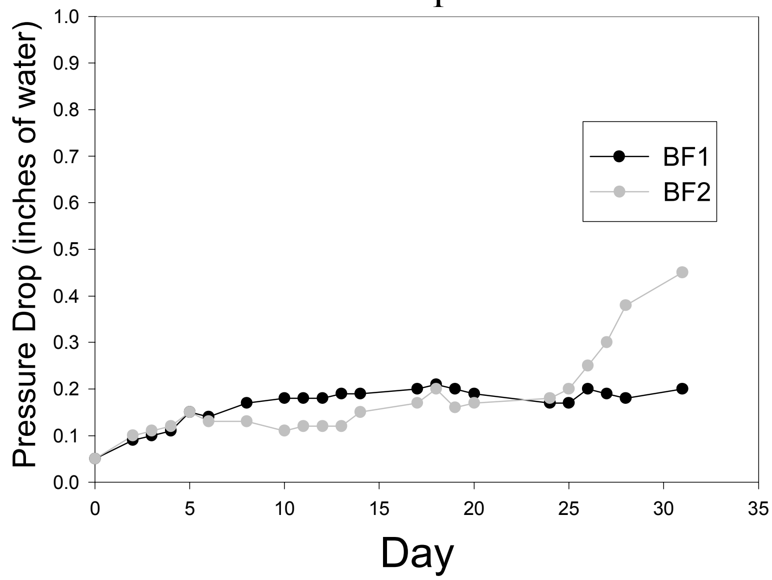


These levels dropped to 40 g/L for the remainder of the experiment. The degree of fluctuation was probably due to differences in batches of feedstock. This compost used the carbon source more efficiently than the other composts did. Effluent levels of both lactate and acetate remained low throughout the experiment. The breakdown products of lactate were also used very efficiently. In BF2, effluent lactate and acetate concentrations increased for one day on day 27. The cause of this is unknown. Effluent lactate and acetate concentrations seemed to be unaffected by the presence of oxygen in BF2 on days 19-24.

Microbial Analysis: Microbial data was not collected during this experiment.

Other Physical parameters: Temperatures in the biofilters remained fairly constant throughout the experiment. Air added into BF2 on days 18-24 was not pre-heated before introduction into the biofilter. As a result, the temperature of the water bath increased slightly to compensate for the decreased influent gas temperature while the air was being added. The flow rate in the biofilters started at about 10 L/min and slowly increased until it leveled off at about 11 L/min for the remainder of the experiment. Pressure drop was very low (< 0.20 in. of water) through the first 25 days of the experiment (Figure 4). For

Figure 4: Pressure Drop
Nature Grow Compost

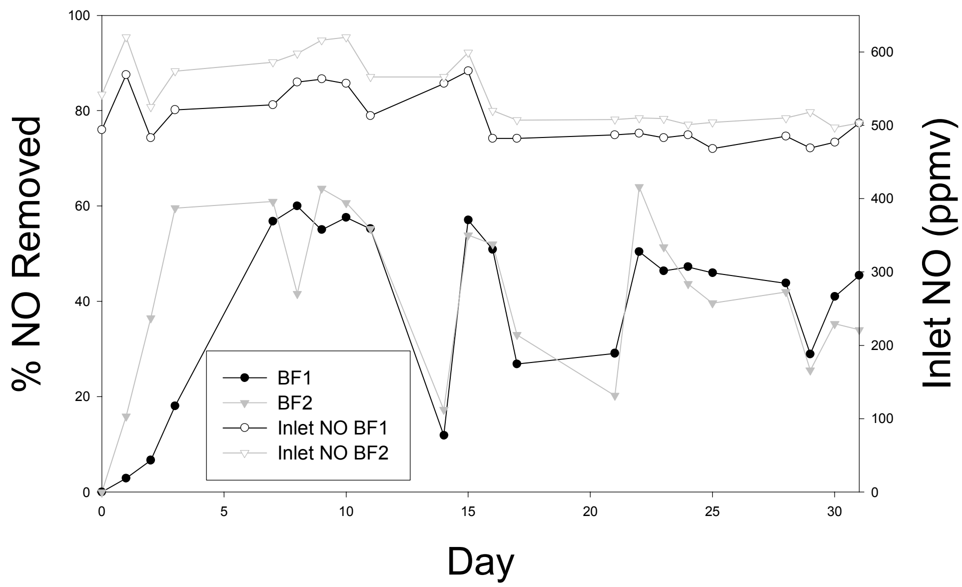


days 25-31, BF2 had a rapid increase in the pressure drop, while levels remained unchanged in BF1. Although somewhat variable, effluent volumes in both biofilters remained around 1 L/day throughout the experiment. There was no appreciable methane production for the first 10 days of the experiment. Methane levels rapidly increased and stayed elevated for the remainder of the experiment. Methane production in BF2 was lower on days 19 and 20 due to the presence of oxygen in the biofilter.

Glacier Gold Compost, Frozen Sample (GG1), Olney, MT

NO Removal Efficiency: NO removal efficiencies were lower than anticipated throughout the experiment (Figure 5). This compost seemed to take longer to reach its

Figure 5: NO removal efficiencies
Glacier Gold 1

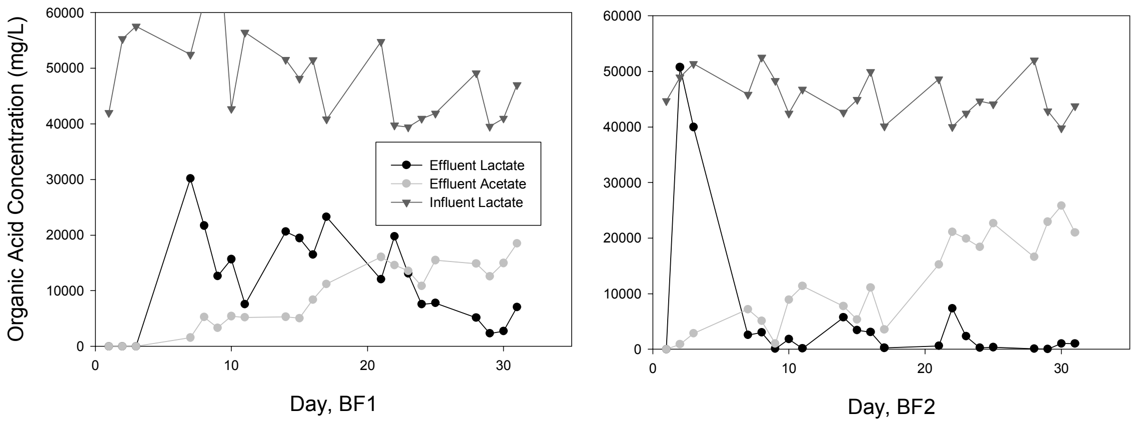


initial NO removal peak. NO removal did not peak in BF1 until day 8 (59.98%) and until day 9 in BF2 (63.64%). On day 13, CO_2 ran out and there was a sharp decrease in NO removal efficiencies. When CO_2 was turned back on, efficiencies returned to previous levels. While removal efficiencies were already low, a sharp increase in pressure drop caused the NO removal to further decrease in BF2 on day 21. After the problem was rectified, there was a sharp increase in removal efficiencies. At this time there was also an increase in removal efficiency in BF1. NO removal efficiencies started out lower than expected, gradually increased to a near maximum removal and then decreased slowly throughout the remainder of the experiment.

pH of Liquid Influent and Effluent*:* The pH of the liquid influent remained very constant, with the exception of an increase in pH on day 14 which was thought to be due to differences in batches of feedstock. After initiation of the experiment, the pH in the liquid effluent took about 7 days to reach neutral levels. The pH in the effluent remained close to neutral in both biofilters throughout the remainder of the experiment.

Organic Acid Analysis*:* Lactate concentrations of the influent feedstock in BF1 were fluctuated between 40 and 60 g/L for the entire experiment (Figure 6). Concentrations in BF2 were typically between 40 and 50 g/L. The degree of fluctuation was probably due to differences in batches of feedstock. This compost seemed to use the carbon source less efficiently than NGC. In BF1, effluent lactate levels remained somewhat elevated through most of the experiment, while BF2 began utilizing a majority of the lactate by day 7. Effluent acetate concentrations started out low in each biofilter and increased slowly throughout the experiment.

Figure 6: Influent and effluent organic acid concentrations Glacier Gold 1



***Microbial Analysis**:* There was very little difference noted in microbial densities throughout the experiment (Table 2). Concentrations of aerobic and anaerobic bacteria were 1.22 x 10^6 and 1.02 x 10^6 CFU's per gram of unacclimated compost, respectively. There were no statistically significant changes in microbial density throughout the experiment, and no apparent trend in differences in density of aerobic and anaerobic microbial populations.

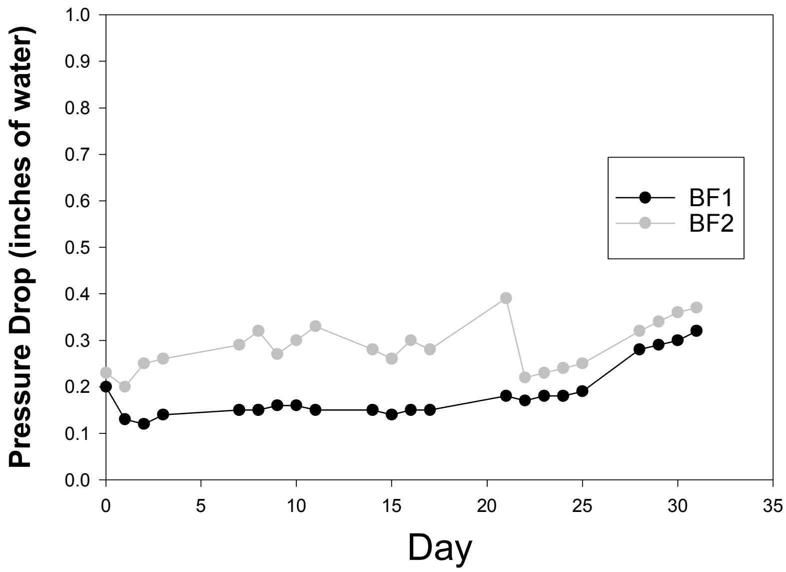
Table 2: Microbial Densities, GG1.

Aerobic	**Top**	**Middle**	**Bottom**
Day 0	1.22e+6 ± 5.66e+4	1.22e+6 ± 5.66e+4	1.22e+6 ± 5.66e+4
Day 10	2.12e+7 ± 3.04e+6	4.95e+5 ± 7.78e+4	1.87e+6 ± 4.95e+5
Day 20	6.30e+5 ± 8.49e+4	2.45e+5 ± 7.07e+3	3.00e+5 ± 7.07e+4
Day 30	6.10e+5 ± 1.13e+5	1.84e+7 ± 4.24e+6	3.05e+6 ± 4.95e+5

Anaerobic	**Top**	**Middle**	**Bottom**
Day 0	1.02e+6 ± 1.06e+5	1.02e+6 ± 1.06e+5	1.02e+6 ± 1.06e+5
Day 10	7.70e+6 ± 4.24e+6	5.45e+5 ± 2.05e+5	2.20e+5 ± 0.00
Day 20	7.50e+4 ± 7.07e+3	3.64e+6 ± 6.79e+5	1.03e+6 ± 2.19e+5
Day 30	N/A	N/A	N/A

***Other Physical Parameters**:* Temperatures and flow rates in the biofilters remained very constant throughout the experiment. The pressure drop in both biofilters was higher than in other experiments (Figure 7). By day 21, the pressure drop in BF2 became so high, that the biofilter was run in reverse flow mode in order to reduce the pressure differential. When this was done, about 500 ml of liquid effluent was removed and the pressure drop decreased sharply. At the end of the experiment, pressure drop in both biofilters was steadily increasing. The experiment was ended before additional remedial activities were necessary. Once the biofilters had stabilized, liquid effluent volumes remained near or slightly above 1 L/day for the duration of the experiment. There were no large amounts

Figure 7: Pressure Drop
Glacier Gold 1

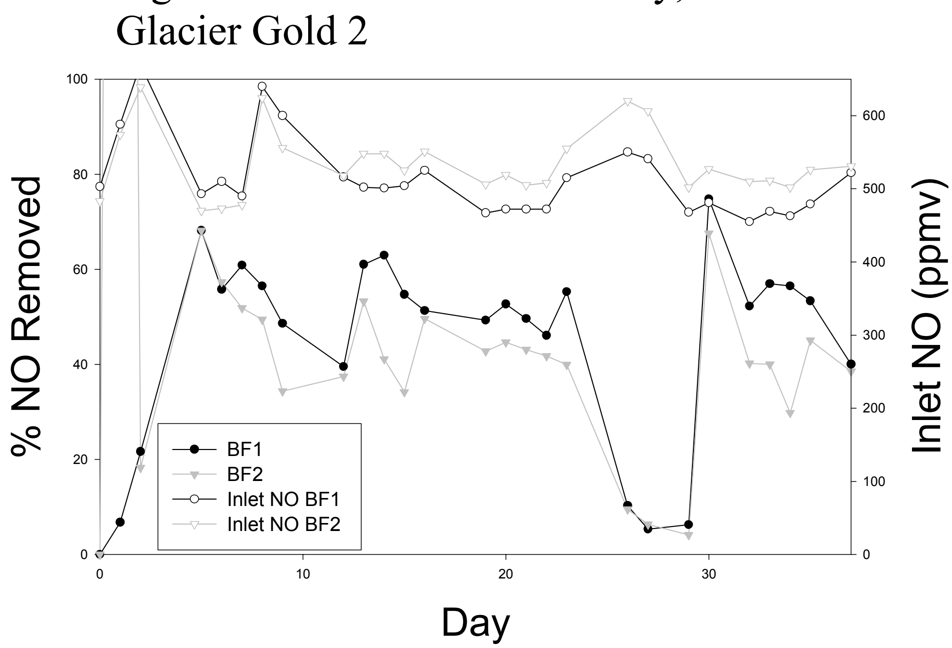


of methane produced in either biofilter for the first 8-9 days of the experiment. Methane levels in BF2 started to increase rapidly, but then decreased sharply due to the loss of CO_2 from the system on day 13. When the CO_2 was turned back on, methane production again increased rapidly in BF2 and remained high throughout the experiment. Initiation of methane production in BF1 was slower and much lower than that seen in BF2, requiring nearly 15 days before a sharp and steady rise in methane production could be measured.

Glacier Gold Compost, Fresh Sample (GG2), Olney, MT

NO Removal Efficiency: NO removal efficiencies were again lower in this compost throughout the experiment (Figure 8). Initial NO removal efficiency peaks (BF1 and BF2

Figure 8: NO removal efficiency, GG2

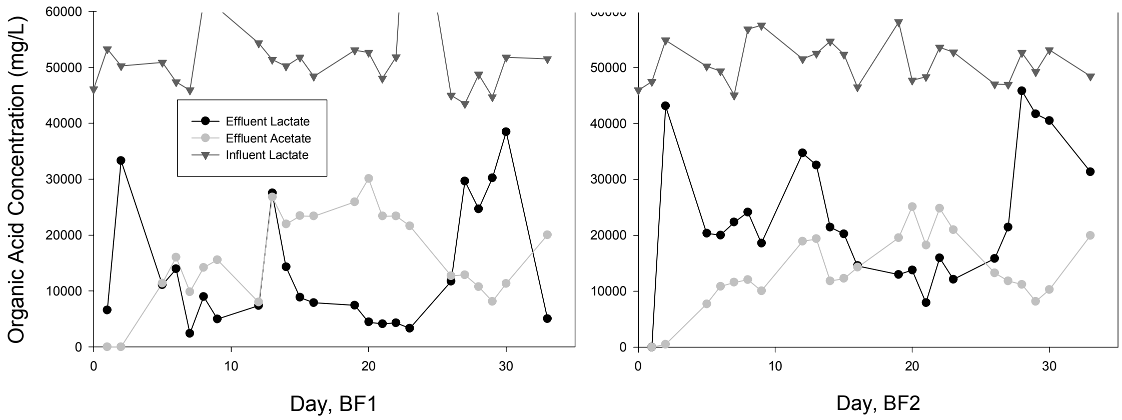


at 68.14% and 68.15, respectively) were not seen until day 5 of the experiment. Removal efficiencies were very similar between the two biofilters throughout a majority of the experiment. After the initial surge of NO removal, levels dropped off, but typically remained above 40%. On day 27, the CO_2 ran out causing NO removal efficiencies to decrease dramatically. CO_2 was turned on after sampling was completed on day 29. On day 30, there was a surge in NO removal in both biofilters, however by day 32, removal efficiencies were at levels similar to those prior to the interruption. In general, NO removal efficiencies decreased during the experiment, however this drop in efficiency was smaller than that seen in other experiments.

pH of Liquid Influent and Effluent: The pH of the influent feedstock once again varied slightly due to small differences between batches. The pH of the liquid effluent started out slightly acidic, but as the biofilters stabilized, the pH approached neutrality. The pH in the effluent did not seem to be affected by the loss of CO_2 from the gas mixture.

Organic Acid Analysis: Lactate concentrations of the influent feedstock in both biofilters were typically between 40 and 60 g/L for the entire experiment (Figure 9). The degree of fluctuation was probably due to differences in batches of feedstock. Effluent lactate concentrations remained fairly low in BF1 through most of the experiment, while levels were roughly twice as high in BF2. There was a brief increase in effluent lactate concentrations in both biofilters late in the experiment that seemed to coincide with the loss of CO_2 on days 26-29. Throughout the experiment, effluent acetate concentrations were also somewhat elevated when compared to those in NGC. There seemed to be a brief decrease in acetate concentrations late in the experiment. This was probably due to a decrease in lactate metabolism rather than an increase in lactate usage efficiency.

Figure 9: Influent and effluent organic acid concentrations Glacier Gold 2



***Microbial Analysis**:* As with previous experiments, there was very little difference noted in microbial densities throughout the experiment, especially for those cultured under aerobic conditions (Table 3). Concentrations of aerobic and anaerobic bacteria were 2.02 x 10^7 and 1.51 x 10^7 CFU's per gram of unacclimated compost, respectively. There were no significant differences between anaerobic and aerobic microbial density and little change in density over the duration of the experiment.

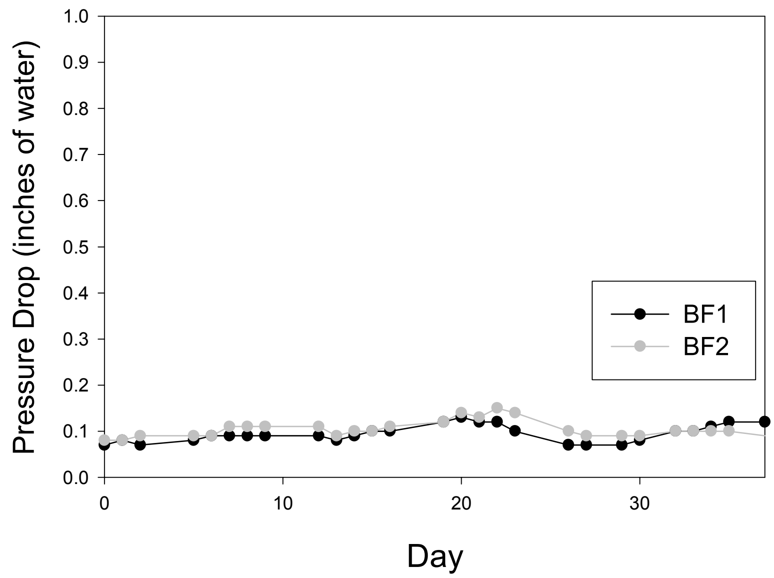
Table 3: Microbial Densities, GG2.

Aerobic	**Top**	**Middle**	**Bottom**
Day 0	2.02e+7 ± 1.14e+6	2.02e+7 ± 1.14e+6	2.02e+7 ± 1.14e+6
Day 10	8.00e+6 ± 1.21e+6	3.83e+6 ± 2.28e+6	3.23e+6 ± 1.76e+6
Day 20	N/A	1.43e+8 ± 6.43e+7	4.97e+7 ± 4.73e+6
Day 30	1.99e+7 ± 4.55e+6	1.36e+7 ± 2.47e+6	5.80e+6 ± 4.06e+6

Anaerobic	**Top**	**Middle**	**Bottom**
Day 0	1.51e+7 ± 9.90e+5	1.51e+7 ± 9.90e+5	1.51e+7 ± 9.90e+5
Day 10	1.05e+7 ± 7.55e+5	9.77e+6 ± 2.63e+6	2.97e+6 ± 9.07e+5
Day 20	3.97e+7 ± 9.07e+6	1.53e+7 ± 3.21e+6	1.05e+8 ± 1.77e+7
Day 30	3.43e+7 ± 7.09e+6	4.67e+6 ± 1.10e+6	3.43e+6 ± 1.33e+6

Other Physical parameters*:* Temperatures within the biofilters remained very close to 55°C throughout the experiment. The top of BF2 was always slightly colder (~52°C) than the rest of the biofilter. The flow rate in both biofilters remained around 12 L/min. except when the CO_2 ran out. The pressure drop increased only slightly throughout the experiment, and decreased when the CO_2 ran out (Figure 10). Both the flow rate and

Figure 10: Pressure Drop
Glacier Gold 2



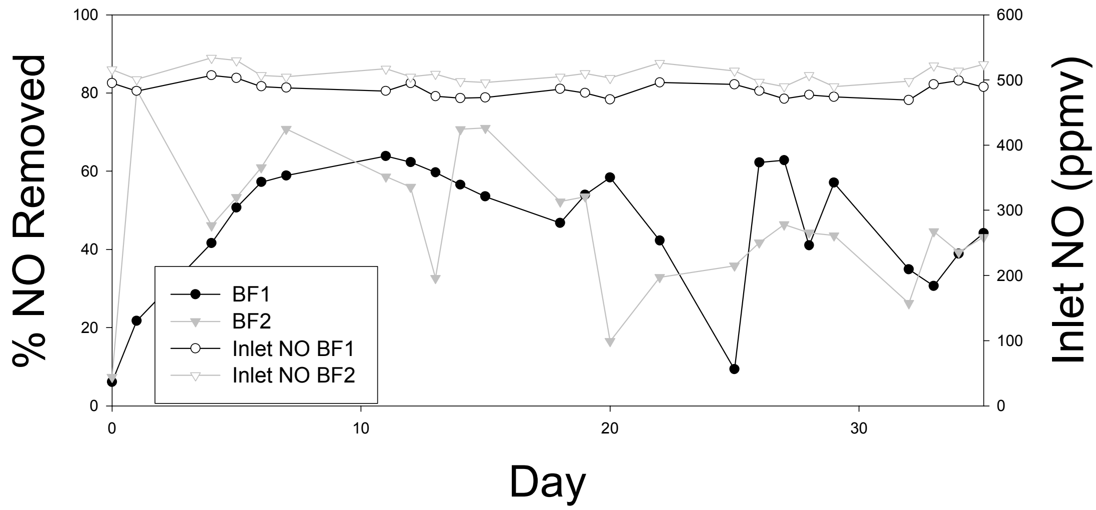
pressure drop in the biofilters returned to normal levels after the CO_2 was turned back on. Liquid effluent volumes remained between 1 and 2 L/day for most of the experiment. Methane was not detected until day 16 in this experiment. Methane production decreased sharply after day 22 of the experiment due to lack of CO_2 in the gas mix, but recovered quickly after the CO_2 was turned back on.

Mountain Dairy Compost (MD), Duchesne, UT

The operation of these biofilters proved to be more problematic than others tested. Both biofilters were run in reverse flow mode on a routine basis to alleviate elevated pressure drops. There was also a system failure in BF2 that caused the humidifier to lose temperature and the biofilter to dry out.

***NO Removal Efficiency**:* NO removal efficiency in BF2 surged to 80.74% after less than 24 hours (Figure 11). However on the next sampling date (day 4), this had decreased to

Figure 11: NO removal efficiency
Mountain Dairy

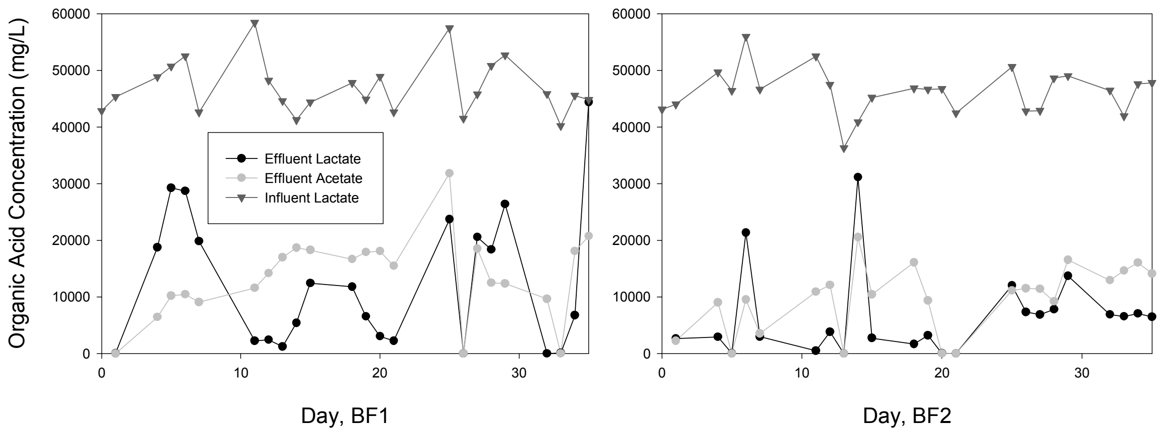


46.11%. Before sampling on day 4, CO_2 had run out for about 10 minutes. It is uncertain if this could have caused the observed decrease. Removal efficiencies in BF2 increased over the next four days to 70.81% then decreased. On day 13, the pressure drop in BF2 increased causing NO removal to decrease. On day 20, the water bath was too cold to deliver heat and humidity to the influent gas stream. As a result, the heater on the biofilter had to compensate for this and was too hot. With a lack of humidity, NO removal efficiencies dropped to 16.53%. Temperature regulators were adjusted accordingly and NO removal efficiencies recovered slightly. NO removal efficiencies in BF1 climbed very slowly and reached their peak (63.83%) on day 10. Removal efficiencies decreased slowly until day 25 when they dropped sharply as the pressure drop became too high. The system was run in reverse flow mode and the following day, the removal efficiencies recovered.

***pH of Liquid Influent and Effluent**:* The pH of the liquid influent remained constant throughout the experiment. The pH of the liquid effluent was more temperamental and changed as parameters within the biofilter changed. On day 5, the effluent from BF2 was nearly clear, most likely resulting from condensation of the humidity in the gas stream. This effluent never interacted with the compost mixture, thus having a pH similar to that of distilled water. This was fixed by adjusting the temperature controllers. On day 13 for BF2 and days 25 and 33 for BF1, the decreased pH was due to increased pressure drop in the biofilters and subsequent condensation in the liquid effluent. On day 20, the decreased pH was due to the system failure previously mentioned. In all cases, when the pH of the liquid effluent was below 6.5, the effluent was clear or nearly clear and colorless.

***Organic Acid Analysis**:* Lactate concentrations of the influent feedstock in both biofilters were typically between 40 and 50 g/L for the entire experiment (Figure 12). Inlet lactate

Figure 12: Influent and effluent organic acid concentrations Mountain Dairy



concentration in both biofilters seemed to be more variable in this experiment. The degree of fluctuation was probably due to differences in batches of feedstock. The instability of the pressure drop in both biofilters and the system failure in BF2 on day 20 led to highly variable effluent organic acid concentrations. Effluent lactate concentrations were highly variable and decreases seemed to coincide with increases in pressure drop. After increased pressure drop events were remedied, there was a surge of lactate in the next day's effluent, making it difficult to determine normal levels. There were two surges on days 6 and 14, both corresponding to increases in pressure drop. As the system failed in BF2 on day 20, there was no effluent flowing through the biofilter. Acetate concentrations in BF1 seemed to be less affected by increases in pressure drop, while in BF2 acetate concentrations decreased as pressure drop decreased. All things considered, this compost seemed to use the organic acids less efficiently than NGC.

***Microbial Analysis**:* Again, there was very little difference noted in microbial densities throughout the experiment (Table 4). Initial aerobic microbial densities were higher than aerobic densities for the other 3 composts tested. Unacclimated compost contained 3.43 x 10^8 CFU's per gram for aerobes and 1.07 x 10^6 CFU's per gram of unacclimated compost for anaerobes. Although there were a few statistically significant changes over the duration of the experiment, there was no apparent trend of microbial activity, when comparing aerobic to anaerobic microbial densities.

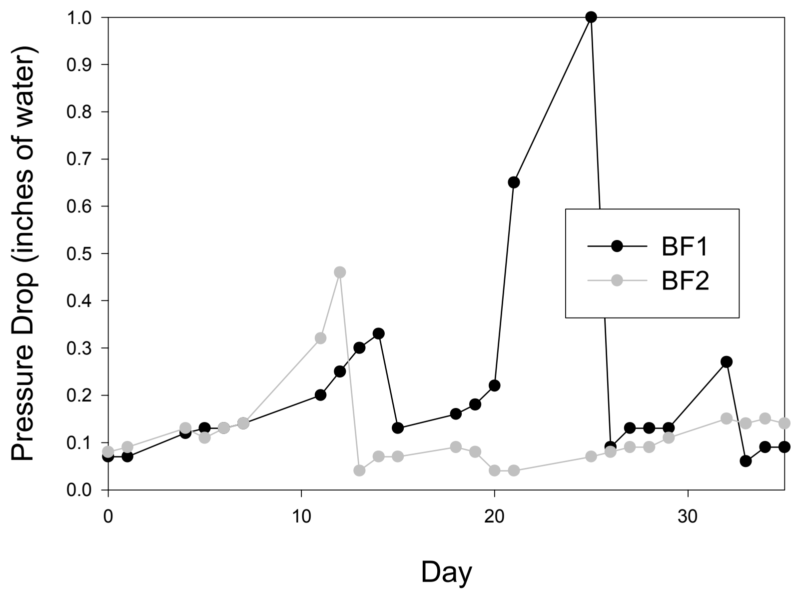
Table 4: Microbial Densities, MD.

Aerobic	Top	Middle	Bottom
Day 0	3.43e+8 ± 5.13e+7	3.43e+8 ± 5.13e+7	3.43e+8 ± 5.13e+7
Day 10	1.69e+8 ± 2.26e+7	2.59e+8 ± 1.48e+7	8.80e+8 ± 1.59e+8
Day 20	1.63e+8 ± 8.02e+7	6.10e+8 ± 1.56e+8	2.03e+8 ± 5.51e+7
Day 30	1.25e+8 ± 1.41e+7	6.93e+7 ± 2.08e+6	1.05e+8 ± 1.21e+7

Anaerobic	Top	Middle	Bottom
Day 0	1.07e+7 ± 2.58e+6	1.07e+7 ± 2.58e+6	1.07e+7 ± 2.58e+6
Day 10	1.20e+7 ± 4.67e+6	9.10e+7 ± 8.06e+7	7.40e+6 ± 4.45e+6
Day 20	2.77e+6 ± 1.50e+6	2.30e+6 ± 8.19e+5	3.50e+6 ± 9.64e+5
Day 30	2.37e+6 ± 2.52e+5	6.33e+5 ± 1.53e+5	1.43e+6 ± 1.53e+5

***Other Physical parameters**:* Except for the system failure in BF2 on day 20, the operating temperatures in the biofilters remained fairly constant. The flow rate in this experiment (about 11.5 l/min) was slightly below targeted values. The flow rate did however remain fairly constant throughout the experiment. Elevated pressure drop proved to be problematic in this experiment (Figure 13). Remediation of pressure drop in

Figure 13: Pressure Drop
Mountain Dairy



BF 1 was performed on days 14, 21, and 25, while BF2 was done on day 12. Pressure drop again started to increase in biofilter 1 on day 32, however this was fixed by decreasing the humidifier temperature by 2°C. All increases in pressure drop were due to large amounts of moisture accumulating within the biofilter column. As the increased pressure drop in the biofilters was remediated, anywhere from 100 to 500 ml of liquid effluent was collected. Effluent volumes produced by the biofilters were somewhat constant, with most measurements showing around 1 L/day. Decreased were seen in effluent volumes in BF2 on days 13 (increased pressure drop) and 20 (system failure, dry biofilter). After humidifier was turned up on BF2 to fix the system failure, effluent volumes increased to about 1.5 L/day. Methane production began to increase in both biofilters after day 4. Decreases in methane production for BF2 seen at day 13 and for BF1 at days 25 and 33 were all due to increases in the pressure drop. Low methane production levels at day 20 were due to a lack of humidity in the column caused by the system malfunction.

General Comparison of Composts

Although the decreased NO removal efficiencies do not seem to be compost related, compost selection is an important consideration in designing a biofilter. The initial removal efficiencies varied greatly and usually represented the maximum. MD had the highest starting point, followed by NGC, then GG2 and GG1. It is interesting to note that the lowest performer (GG1) was frozen when received. The freezing of GG1 could have had irreversible effects on the denitrifying population. NGC and GG2 were both used within a few days after being taken from an active compost pile while MD had been in retail packaging for an indeterminate amount of time.

It is also notable that the two lowest performers (GG1 and GG2) were wood based with a high nitrogen content sludge. The C:N ratio for each of (9:1 and 4:1, respectively) these was considerably lower than that of NGC (36:1) and MD (17:1). Biofilters with low NO removal efficiencies typically also exhibited inefficient lactate conversion. As NO removal decreased, increasing amounts of lactate and acetate accumulated in the effluent. Results from the current comparison of composts indicate that compost with high carbon to nitrogen ratios should be selected as the raw material for bed medium packing for biofiltration of NO.

CONCLUSIONS

The NO removal efficiencies of each compost tested decreased as the experiment proceeded, suggesting that the problem of decreasing removal efficiencies is not related to the compost type or source, but it is related to some characteristic which these composts all have in common. It was observed that the color of the effluent liquid changed throughout the experiment. Early in the experiments, the liquid was a very dark brown color, but as the experiments proceeded, the color changed to amber or light brown, then to a cloudy, off-white color. The dark color of the effluent liquid could be attributed to soluble humics. As more liquid washed through the compost packing, the humics were washed away and not replenished. It has been shown that humics could be used as electron donors for denitrification[11]. So it is possible that as humics are lost from the compost, so also is the ability to denitrify. Experiments to test this hypothesis are currently in progress. This decrease in NO removal efficiencies could also be explained by the loss of other nutrients that are metabolized or washed out of the biofilter early in the experiment.

ACKNOWLEDGEMENTS

This research was supported through the U.S. DOE, Office of Advanced Research and Technology Development, Office of Fossil Energy under DOE Idaho Operations Office Contract DE-AC07-94ID13223. Compost was supplied by Nature Grow Compost, Pocatello, ID, Glacier Gold Compost, Olney, MT, and Mountain Dairy Compost, Duchesne, UT.

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